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Redstone Arsenal, Alabama 35898-5280

Attn: Ms. Tandy Lane, Project Manager

Dear Ms. Lane:

Following is our Final Report reflecting Quatro's activities on contract number DAAH01-94-C-R285.

Sincerely,
Quatro Corporation

David E. Thomas

David E. Thomas
Technical Director

DET/mac
Enclosures: as stated

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Under Contract Number DAAH01-94-C-R285, Quatro Corporation has developed a fully-functional, automated silicon nitride Bearing Ball Inspection Station which utilizes Resonant Inspection (Resonant Inspection) to determine if the balls are flawed or acceptable. The Bearing Ball Inspection Station was demonstrated at the Norton Advanced Ceramics facility in East Granby, Connecticut in October of 1995. The station was succesful in finding flaws in several sizes of silicon nitride bearing balls, although more work remains to be done as regards optimization of the system to avoid false rejects.

The report describes the background of Resonant Inspection testing (Section 1), the automated Bearing Ball Inspection Station (Section 2), results of Resonant Inspection testing with the station (Section 3), and conclusions and recommendations (Section 4).

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FINAL REPORT

AUTOMATED SILICON NITRIDE BEARING BALL INSPECTION STATION

February 26th, 1996

Sponsored by:

Advanced Research Projects Agency (DoD)
U.S. Army Missile Command
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Redstone Arsenal, Alabama 35898-5280

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Prepared by:

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Effective Date of Contract: 10-94
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Short Title: Automated Silicon Nitride Bearing Ball Inspection Station

1.0. SUMMARY

Under Contract Number DAAH01-94-C-R285, Quatro Corporation has developed a fully-functional, automated silicon nitride Bearing Ball Inspection Station which utilizes Resonant Inspection (Resonant Inspection) to determine if the balls are flawed or acceptable. The Bearing Ball Inspection Station was demonstrated at the Norton Advanced Ceramics facility in East Granby, Connecticut in October of 1995. The station was successful in finding flaws in several sizes of silicon nitride bearing balls, although more work remains to be done as regards optimization of the system to avoid false rejects.

The remainder of this report describes the background of Resonant Inspection testing (Section 1), the automated Bearing Ball Inspection Station (Section 2), results of Resonant Inspection testing with the station (Section 3), and conclusions and recommendations (Section 4).

2.0. BACKGROUND

The use of mechanical resonances to test the properties of materials is as old as the industrial revolution. The earliest attempts to use resonances involved engineers tapping the wheels of a train and listening to the response to qualitatively assess their integrity. This is based on the observation that if continuous acoustical energy (sound) is applied to an object, it will resonate, or ring, just like a bell, when the sound frequency matches one of the object's natural vibrational frequencies. At resonance, the object behaves like a natural amplifier and increases the amplitude of its vibrations. An object exhibits many resonances, which are determined by its shape, size, density and material properties (such as the elastic moduli). Any deviation from the norm (such as a crack, inclusion, scratch, dimensional change, etc.) changes the resonance spectrum.

Until the invention of Resonant Inspection (RI), resonance measurements were insufficiently accurate for use in most industrial applications. In the late 1980s Dr. Albert Migliori, at Los Alamos National Laboratory, extended electronic and transducer technology to the point where industrially useful measurements were possible. He integrated these improved components into the patented Resonant Ultrasound Inspection system. The essence of the RI technique is to measure resonances across a broad spectrum and to select the resonances which correlate to the physical property of interest. This correlation is embodied in an algorithm which allows a microcomputer to pass or fail components based on any deviation from the desired quality.

Quatrosonics recognized the potential for RI application to non-destructive testing, licensed it from Los Alamos, and completed product development, including the RI algorithms which are proprietary Quatrosonics products. In non-destructive test applications, RI offers three important advantages over existing methods:

- since RI measures a part's mechanical properties, it provides a quantitative, objective measure of the part's "defectiveness", that is the degree to which a selected parameter (e.g., stiffness or a dimension) differs from the acceptable norm. This contrasts to a technique such as dye penetrant which provides only a superficial indication of the defect and requires human judgment to interpret.
- since RI testing is rapid (as little as one second, plus material handling time, per part) and inexpensive, 100% parts testing is feasible.
- RI measurements are repeatable, requiring no operator intervention or judgment.

These advantages are particularly important for engineered materials such as ceramics or composites which are used in extreme environments. For this application, certain high-frequency modes which are localized to the surfaces of the balls (Rayleigh Surface Acoustic Wave modes, or "SAW modes" were employed for detection of surface defects.

The RI technology is embodied in the Quatrosonics RI-1000. The controller computer, pick-and-place head, materials handling hardware, QS-20 receivers, and transducer nest comprise a flexible system that can be configured for use in either the laboratory or the factory.

2.0. DESCRIPTION OF AUTOMATED SILICON NITRIDE BEARING BALL INSPECTION STATION

The various components of the Automated Bearing Ball Inspection Station (materials handling hardware / software, resonant inspection hardware / software, and manual controls) were integrated into a fully functional system, which appears in Figure 1. The Hardware Console appears at the left of the figure: this contains manual controls for test start, test stop, jog, etc., and supports the Personal Computer Monitor (not required for production testing). The interior of the Console contains the computer controller, motion controllers, and associated hardware. The Materials Handling / Resonant Inspection / Ball Sorting table appears at the right of Figure 1, and enlargements of the Table appear in Figure 2 and Figure 3. The Table consists of a ball feeder bin (at the left of the table surface), ball pick-and-place apparatus, a Resonant Inspection test nest (directly under the pick-and-place head), an output gate, and two output bins. The rear output bin (Figures 2 and 3) receives "acceptable" balls, while the front, smaller bin receives "rejectable" balls (as determined by Resonant Inspection).

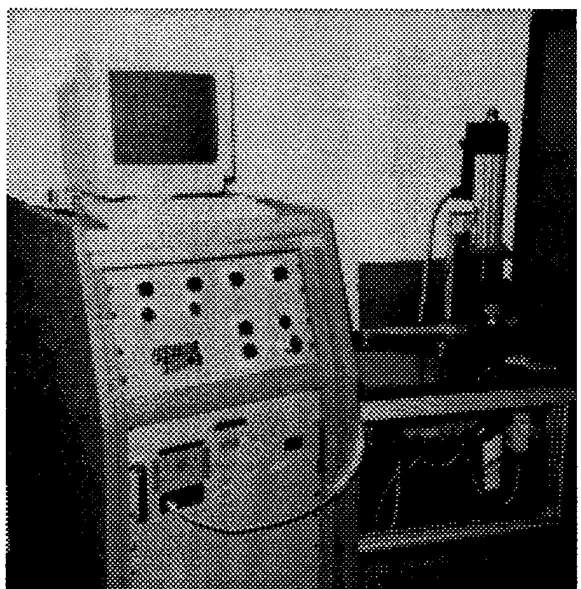

Figure 1. Automated Bearing Ball Inspection Station: Manual Controls / Hardware Console / PC Monitor appear at Left, and Materials Handling / Resonant Inspection / Ball Sorting table appears at Right.

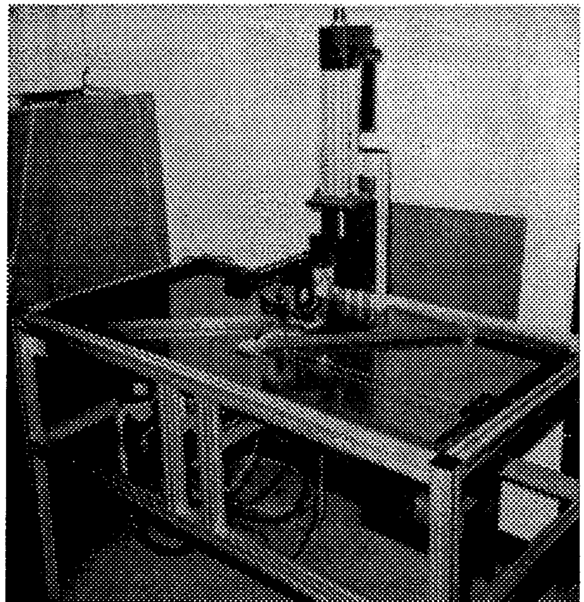

Figure 2. Automated Bearing Ball Inspection Station: Materials Handling / Resonant Inspection / Ball Sorting table.

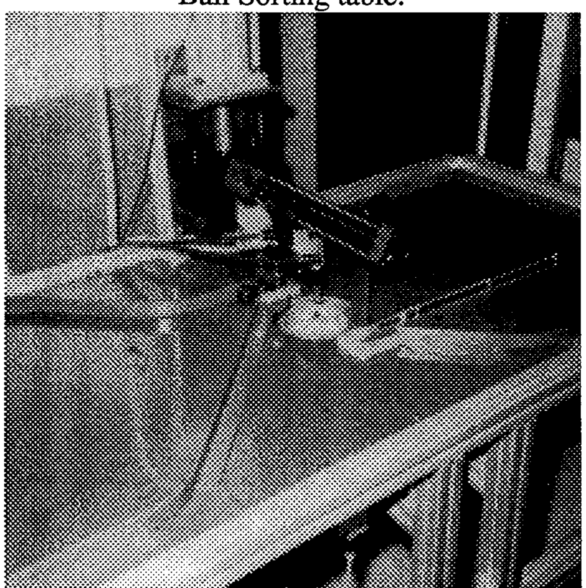

Figure 3. Detail of Automated Bearing Ball Inspection Station: Materials Handling / Resonant Inspection / Ball Sorting table.

In production, balls are loaded into the feeder bin, which has a shaker to keep the balls moving along into place. Upon test initiation, the two-axis pick-and-place apparatus takes a ball from the feeder bin, and simultaneously takes a ball from the Resonant Inspection (RI) nest to the output gate. The RI low-frequency sweep is performed for the ball placed onto the nest, and the location of the main resonant peak within this window is measured (this corresponds to the second resonant mode, referred to as the 2nd torsional, or T_2 mode). The T_2 mode is then used to determine the high-frequency window corresponding to the diagnostic (surface acoustic wave, or SAW) resonance mode for the ball under test. The T_2 mode frequency is estimated simply via the relationship $f_{T_2}(\text{kHz}) \cong \frac{250.11}{\pi D}\sqrt{\frac{\mu}{\rho}}$, where D is ball diameter (cm), μ is shear modulus

(GigaPascals), and ρ is the density (g/cc). The low-frequency window spans 10 kilohertz (kHz) with 400 data points, and is wide enough to locate the desired T_2 mode over a wide range of ball variations. For 1/2"-diameter balls, this low-frequency modes were measured at 387 - 397 kHz; for the 9/8"-diameter balls, the low-frequency modes occurred at 165 - 180 kHz. For any size ball, the results of several detailed simulations of the resonance behavior of the balls, coupled with very broad-band Resonant Inspection measurements, showed that the high-frequency diagnostic SAW mode (the 102nd resonance, which is 37-fold degenerate) is located at a frequency 7.369 times that of the low-frequency T_2 mode. For 1/2" balls, the diagnostic SAW mode occurs at around 2880 kHz, while for 9/8" balls, the diagnostic mode occurs at around 1280 kHz. The high-frequency window is then swept with 1000 points over a range of 8 kHz; the exact start and stop frequencies of the SAW mode are calculated mid-measurement for each ball tested, thus automatically moving the diagnostic window. The decision algorithm is then employed to decide upon ball status (accept or reject). The flaw indicators are the number of peaks and frequency spread of the peaks in the SAW response region. Good balls will have just a few peaks, with relatively small overall spread, whereas the flawed balls will have more peaks and wider spreads because of the splitting of degeneracies (caused by ball asymmetries due to surface flaws) for the 37-fold-degenerate SAW mode. When the tested ball is subsequently placed at the output gate, the gate is operated according to the results of the corresponding RI test, sending the ball into either the accept or reject bin. The system is fully automatic: the operator can place a number of balls in the feeder bin, press "Start", and return to find the batch of balls sorted according to accept/reject status. The test time for each ball ranges from 3 seconds to 10 seconds, with the longer times resulting from automatic re-sweeping of resonant spectra for over-amplified or under-amplified signals. The system can be quickly reconfigured to test different ball sizes. Both large (9/8"-diameter) and small (1/2"-diameter) balls were tested at the demonstration at the Norton facility.

A schematic of the Automated Bearing Ball Inspection Station hardware configuration appears in Figure 4. The SLOSYN-2001 indexer/controller was used to direct the entire process: pick-and-place head operation, operation of shaker and gates, and issuance of test-start and test-stop instructions to the Resonant Inspection computer controller. A flowchart of the programmable logic control process is shown in Figure 5.

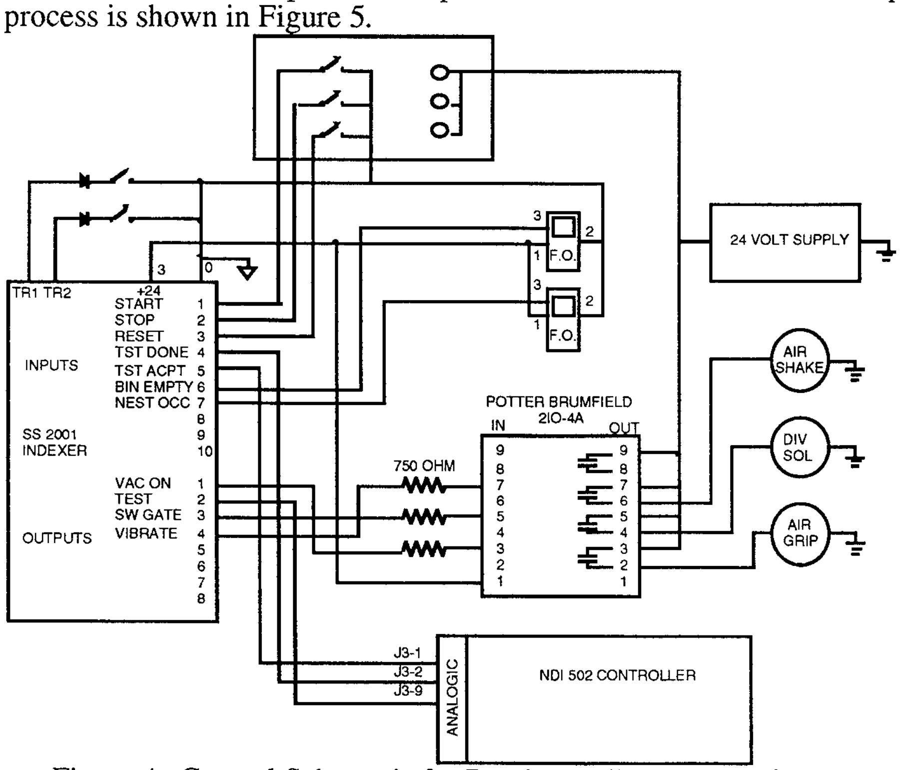

Figure 4. Control Schematic for Bearing Ball Inspection Station

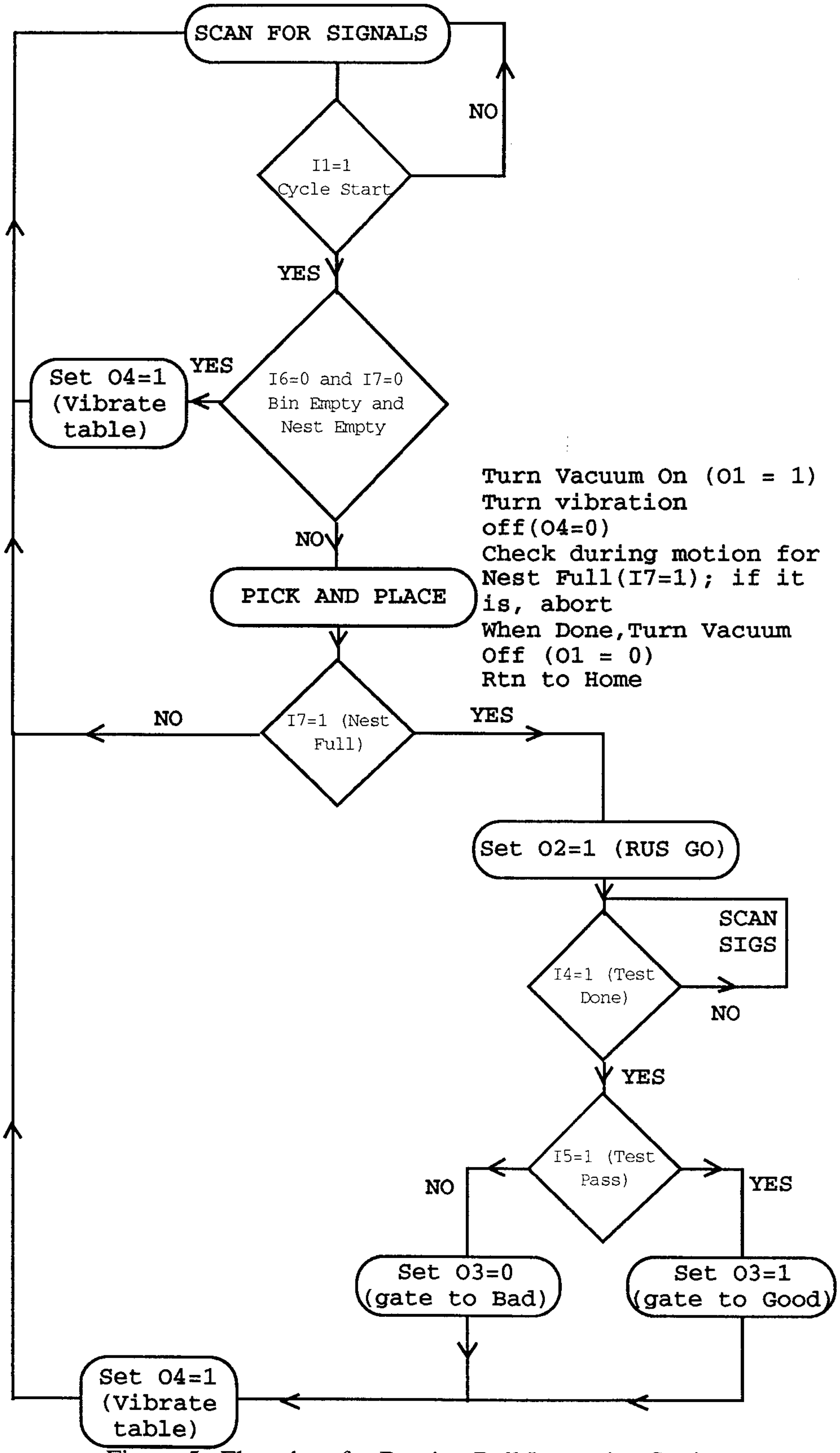

Figure 5. Flowchart for Bearing Ball Inspection Station

3.0. RESULTS OF RESONANT INSPECTION OF BEARING BALLS

The resonant response of typical bearing balls contain literally thousands of vibrational modes. The 102nd such mode attenuates exponentially with depth from the ball surface, and thus is ideal for detection of surface flaws. The location and nature of this Surface Acoustic Wave (SAW) mode was developed as the result of several analyses performed at Los Alamos National Laboratory. For balls with no surface defects, the SAW mode produces just a few resonant peaks close together, as shown in Figure 6. However, for balls with surface defects, the broken symmetry allows many of the superimposed modes (37-fold degenerate) to manifest themselves as numerous peaks with wide separations, as indicated in Figure 7.

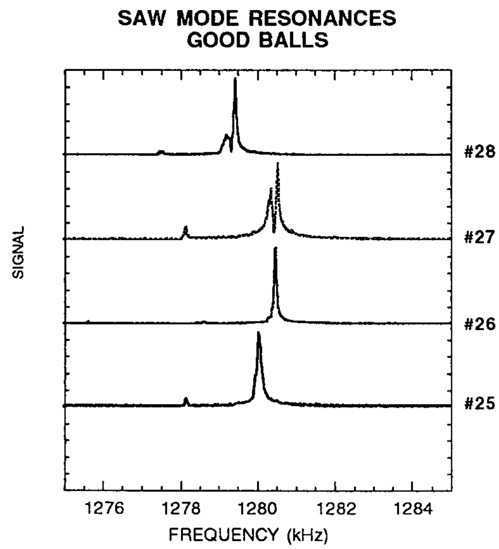

Figure 6. SAW Mode Responses of Selected Good 9/8" Balls

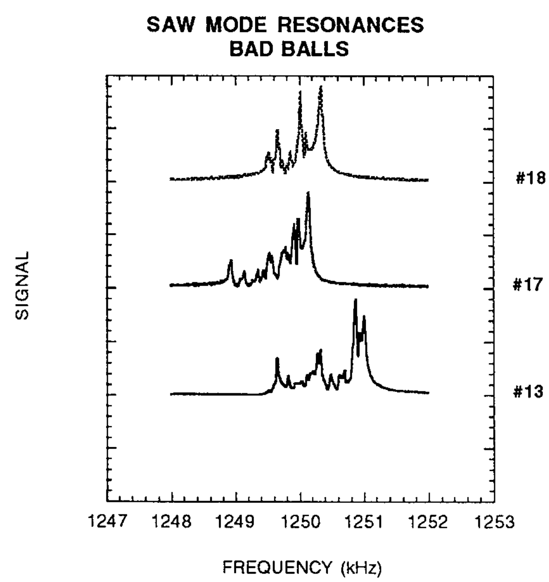

Figure 7. SAW Mode Responses of Selected Bad 9/8" Balls

A comparison of Resonant Inspection measurements of two 9/8" diameter silicon nitride balls appears in Figure 8. The good ball (lower trace) has only three resonant peaks (indicated by triangles), with a spread of 401 Hertz (Hz). The other ball (top trace) was in perfect condition, with the exception of a small induced C-crack. For this specimen, there are five peaks, with more than half again as much peak separation (611 Hz).

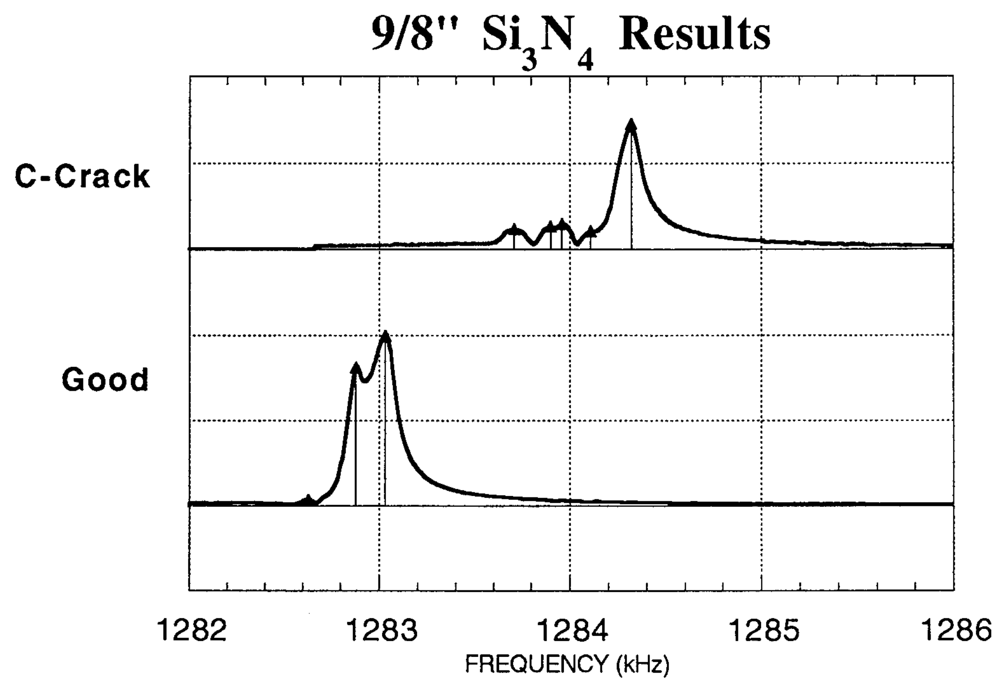

Figure 8. SAW-Mode Responses of 9/8"-Diameter Si_3N_4 Balls: Good (Lower), C-Crack (Upper)

Resonant inspection results for several different half-inch-diameter silicon nitride balls are displayed in Figure 9 below. The SAW modes are more spread out for the good half-inch-diameter balls (bottom three traces) than for the larger balls, but they are spread out considerably more for the damaged half-inch balls (upper four traces). The frequency spreads (maximum intervals) for the good balls are all under 2000 Hz (Good #1: 1537 Hz; Good #2: 1842 Hz; Good #3: 1946 Hz), while the spreads for the flawed specimens are all over 2400 Hz ("chocolate chip" #1: 3676 Hz; "chocolate chip" #2: 3816 Hz; crack #1: 2437 Hz; and Pit #2: 3227 Hz).

Half-inch Si_3N_4 Results

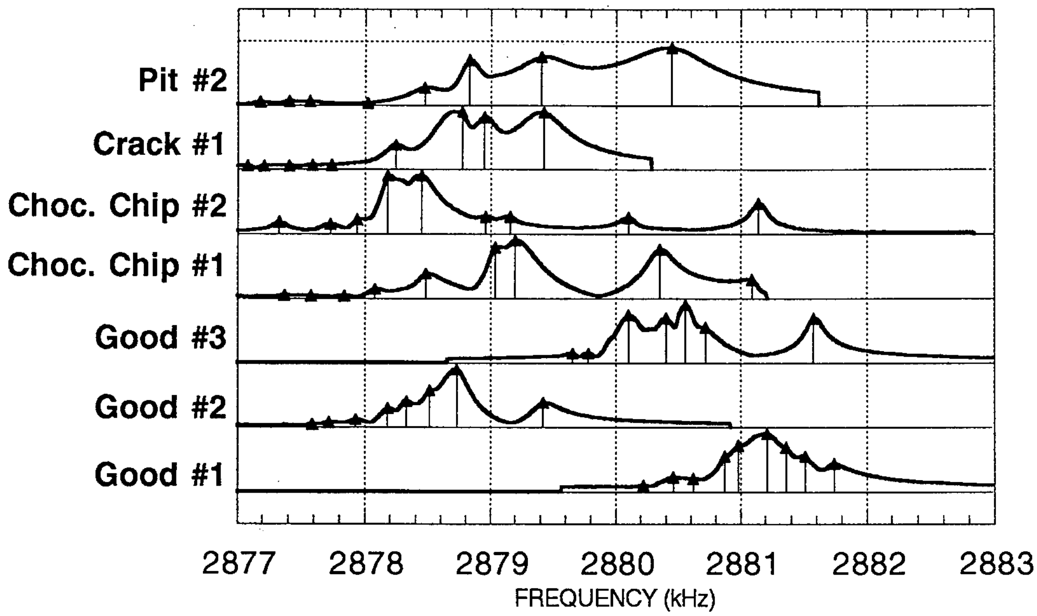

Figure 9. SAW-Mode Responses of 1/2"-Diameter Si_3N_4 Balls: Good (Lower 3 Traces), Flaws (Upper 4 Traces)

Several times during this project, results of Resonant Inspection indicated that certain silicon nitride bearing balls which were thought to be flawless actually had surface flaws. Subsequent microscope investigation (10X - 40X) *confirmed the existence of flaws* on several of these "acceptable" balls. One of the more severe of these flaws shown in Figure 10. This flaw was found to be 175 µm across (about 0.007").

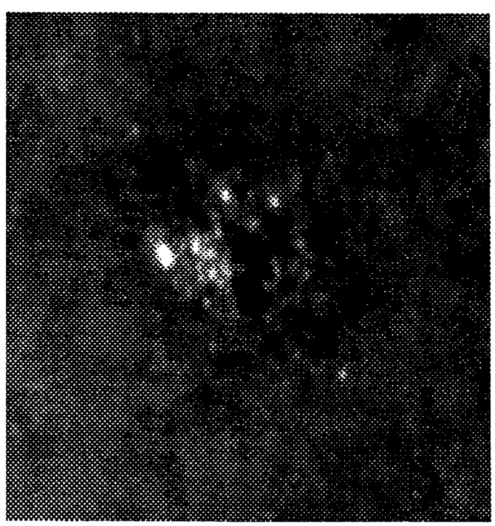

Figure 10. Enlargement of Serious Flaw Found on "Good" Ball

During the demonstration at Norton Advanced Ceramics, one batch of 20 9/8"-diameter balls was tested four times with the automated Bearing Ball Inspection Station. The results of this set of trials were fairly consistent: several balls passed all four tests, several failed all four tests, and a few had mixed results. Subsequent examination of the balls by Norton showed that all of the balls with genuine defects (iron inclusions, low density, etc.) were indeed indicated as flawed by the Resonant Inspection methodology. Several balls, found to be good by Norton, demonstrated Resonant Inspection flaw indications. These negative indications could be due to sensitivity of the test methodology to non-critical aspects of the surface (such as density gradients, fingerprints, etc.), or to sub-surface flaws which were not apparent in the surface inspection process.

4.0. CONCLUSION

The Automated Bearing Ball Inspection Station was developed and demonstrated during the performance of this project. Encouraging results for fully automated, 100% testing of silicon nitride bearing balls were obtained. Further work remains in the quantification of Resonant Inspection indications versus actual flaw size, and in optimization of the equipment false-reject rate.